Mars Pathfinder Flight System Design And Implementation

Brian K. Muirhead
Mars Pathfinder Flight System Manager
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California
818-393-1013
brian.k.muirhead@ccmail.jpl.nasa.gov

Abstract-This paper describes the system architecture, design and implementation approach for the Mars Pathfinder spacecraft scheduled to land on the surface of Mars on July 4, 1997. Mars Pathfinder is one of the new series of small, challenging missions doing significant science/engineering on a fast schedule and cost capped budget.

The Mars Pathfinder spacecraft is actually three spacecraft. The cruise stage carries the entry and lander vehicles to Mars and is jettisoned prior to entry. The entry vehicle protects the hinder during the direct entry and reduces its velocity from 7.6 to O km/s in stages during the 5 minute entry sequence. The lander's touchdown is softened by airbags which are retracted once stopped on the surface, the lander uprights itself, opens up fully and begins surface operations including deploying its camera and rover.

The project is 2 years into its 3 year development cycle with most flight hardware delivered and in system test, This paper overviews the mission design, system architecture and configuration, Descriptions of key subsystems are given, including the entry, descent and landing system elements: aeroshell, parachute, rocket assisted deceleration and airbags. The implementation approach is discussed including the new ways of doing business needed to accomplish this challenging mission within the schedule and cost constraints.

[1] The work described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

TABLE OF *CONTENTS*

INTRODUCTION

The mission objectives of Mars Pathfinder as agreed to with NASA are the following: 1) demonstrate a simple, reliable and low cost system for placing science payloads on the surface of Mars, 2) Demonstrate NASA's commitment ot low cost planetary exploration, 3) demonstrate the mobility and usefulness of a microroer on the surface of Mars and 4) assess the structure of , the Martian atmosphere, determine elemental composition of rocks and soil, investigate surface geology and mineralogy of rocks and acquire data on the surface meteorology.

This paper is written at a point in the project where most flight hardware has been delivered and system test is going well. Adequate budget and schedule reserves appear to be available to complete the project within its original schedule and budget constraints. This paper describes the spacecraft design and implementation approach that have come together to produce what looks to be one of the most exciting and demanding space missions of the last 20 years.

MISSION DESCRIPTION

A single Mars Pathfinder flight system will be launched to Mars in the period December 4, 1996 to December 25, 1996 from a Delta II, landing on the surface of Mars on July 4, 1997. The flight system (shown in Figure 1 in launch configuration) is made up of 3 major elements (shown in exploded view in Figure 2): 1) cruise stage, 2) aeroshell and 3) lander. The flight system is spin stabilized during cruise, spinning at 2 rpm, with the spin axis and medium gain antenna pointed primarily to Earth, The Earth point attitude (within about 40 degrees of the Sun) is maintained until Mars atmosphere entry, except during the first 2 trajectory maneuvers which are performed in turn and burn mode while still in communication with Earth. All cruise critical events are telemetered in real time to Earth.

Thirty minutes before Mars atmosphere contact, the flight system will jettison its cruise stage and enter directly into the Mars atmosphere, braking with an aeroshell, parachute, small solid retrorockets and air bags.

The entry velocity is 7.6 kmlsec(17, 100 mph) compared with Viking at 4.6 km/see which entered from orbit. Mars Pathfinder's entry angle is 15.7 deg. (90 deg. would be straight down) and peak atmospheric deceleration load, 30 g's, is encountered at 32 km above the surface. The parachute is deployed at about Mach 1.8 (900 mph) at 10 km, 100 seconds after atmospheric entry.

During the entry, descent and landing (EDL) phase only the carrier wave will be transmitted to earth. Real time telemetry is not possible due to the highly dynamic nature of the entry events, the various staging events that will cause loss of lock and the low gain available from the descent antennae. Before parachute deployment, Earth remains near the spin axis behind the craft and communication to earth is through a low gain antenna at 40 bps. After chute deployment, the Earth moves to approximately 90 deg. from the spin axis including chute swing, requiring the use of an auxiliary antenna with a side looking pattern. At this time, the S/C will be in carrier detection mode only. EDL, lasting for 5 minutes, will be supported with the 70 m Deep Space Network antenna. Pathfinder lands semi- hard at less than 15 m/s (33 mph) vertical and up to 20 m/s (44 mph) horizontal velocities. Landing loads are limited to <50 g's using an air bag system designed with sufficient stroke to accommodate 1/2 m size rocks. The lander bounces and rolls to a stop and rights itself using 3 actuators which open the petals of the tetrahedral lander like a flower. The petals have solar panels on their inside surfaces, which when exposed to the Sun for power the S/C for surface operations as shown in Figure 3.

After uprighting and opening, the lander will first transmit stored EDL data and real time lander and rover engineering telemetry. If everything is operating nominally, panoramic images of the surface will be also transmitted to Earth the first day over the high gain antenna at at least 1200 bps. In addition, the rover will be deployed on the first day for start of its surface operations. The rover conducts surface mobility experiments, images rocks and soil and deploys the Alpha-X-ray-Proton spectrometer (APXS) on soil and against rocks. Thirty sol and seven sol (1 sol = 24.3 hrs) primary surface missions are planned for the lander and rover, respectively. Close to 100% of all lander and rover engineering and science objectives are achieved nominally in the first few days of surface operations. Currently, no constraints preclude operations of the lander or the rover past their primary mission requirements. Although lifetime is limited due, the limited battery cycle life and thermal cycle induced stress failures of the electronic assemblies.

The Pathfinder scientific payload includes instrumentation for measuring atmospheric and landing deceleration; pressure and temperature during entry and while on the surface; a 12 spectral channel, lander mounted stereo camera for surface and atmospheric imaging, including imaging magnetic properties targets, a wind sock and support of rover navigation; and the rover-deployed APXS for elemental composition measurements of rocks and soil. The rover carries aft and forward cameras for demonstrating autonomous hazard avoidance and imaging its local surroundings, soil and rocks, and the lander.

SYSTEM AND SUBSYSTEM DESCRIPTIONS

The Flight System is made up of 6 major subsystems: 1) Attitude and Information Management (AIM), 2) Power and Pyro Switching (PPS), 3) Telecom (TEL), 4) Mechanical Integration H/W (MIH), 5) Entry, Descent and Landing (EDL) and 6) Propulsion (PRO). The block diagram (Figure 4) shows the elements of the subsystems and their connectivity, Also included are designations showing levels of redundancy and graceful degradation.

The Attitude and Information Management (AIM) subsystem (built primarily at JPL) combines attitude and articulation control and command and data handling functions into a single subsystem. The center of the AIM S/S is a single board 32 bit architecture computer based on the IBM R-6000 (now being developed by Loral Federal Systems Company). This RSC-6000 processor has 128 Mbyte of dynamic RAM and interfaces to all other electronics throught a 32-bit parallel VME bus over a hard backplane.

The rest of the AIM electronics are divided between lander and cruise stage. The lander electronics is containing in a single integrated electronics chassis which is divided into boards on the VME bus and those on a 1553 bus. On the VME bus are a hardware command decoder (HCD) uplink board, a Reed-Solomon Downlink (RSDL) board, 4 Mbyte of in-flight programmable, nonvolatile EEPROM (on two cards) and a camera interface board. On the 1553 bus are the Remote Engineering Unit (REU) for analog measurement acquisition and multiplexing and the lander interface (LIF) board which uses field programmable gate arrays (FPGA's) to interface to sensors. The REU, RSDL, HCD utilize custom ASIC's developed by the Cassini project. Each of the boards in the integrated electronics module is on a 20 by 23 cm aluminum chassis for stiffness and heat dissipation. On the cruise stage is another REU and cruise interface (CIF) board which interfaces to the Adcole sun sensor and Ball Aerospace star tracker.

The flight software uses object oriented design principles and is written in C. The software is stored on 2 Mbyte of EEPROM along with a limited number of sequences and telemetry. A complete back-up version is contained on the 2nd set of EEPROM to allow for recovery from a fault that would cause a reset during a software upload and burnin to the main EEPROM. All flight S/W including attitude control, command and data functions, EDL, camera control and image compression, meteorology and accelerometer control and data processing is developed by a single team of about 8 people. Attitude control algorithms are developed and coded by specialists but are then integrated by the S/W team.

Mechanical Integration H/W (built at JPL) is comprised of the cruise and lander structures which are aluminum machining. Composite structures were considered but the complex interfaces and point loading made composites a poor trade. Very high torque rotary actuators drive the lander petals open with an output torque of greater than 1370 N-m (1000 ft-lb) to overcome gravity from any initial orientation,

The temperature control design is particularly challenging. During launch and cruise the primary problem is to maintain the lander electronics and in particular the battery within flight allowable. The battery life is best maintained if it is kept at approximately -10 to 10 C. Once on the surface, the primary problem is to maintain the electronics above -40 C during the cold Martian night without using a lot of stored energy. This requires thermally isolating the electronics within a very high performance insulation cavity. The temperature control dilemma is how to remove heat during cruise from a well insulated electronics assembly and yet reduce to almost nothing the losses at night on the surface. After studying many passive designs involving heatpipes (variable and fixed conductance) and cutable thermal straps, an active fluid loop heat rejection system (HRS) was baselined. This single phase, redundant pumps, Freon 11 loop carrying >100 watts to a radiator on the cruise stage and is purged just prior to entry.

The Power and Pyro Switching (PPS) S/S provides power from two 5.5 mil GaAs solar arrays (built by ASEC), generating -250w at Mars on the cruise stage and -130w on the lander. The lander carries a >40 A-hr Ag-Zn battery (built by BST) which is a primary battery modified to be used as a secondary for at least 30 cycles of 100% discharge. The bus voltage is control to within 24-36 volts by a shunt regulator. Power control, distribution and pyro switching electronics (built by Loral) employ mechanical relays driven by AIM. The pyro relays, cables and squibs are fully redundant, the drivers are not.

The Telecommunications S/S made up of radio frequency electronics and antennae. The RF elements include: a deep space X-band transponder (DST) (built by Motorola for Cassini), a Command Detector Unit (CDU) (built by JPL), a new development solid state power amplifier (SSPA) utilizing power modules from Avantek, a new development telemetry modulation unit (TMU) which is a full custom ASIC mixing both analog and digital functions on a single chip. The antenna system consists of a stack of low and medium gain antennas and a 2 axis steerable high gain. The LGA/MGA stack go through 3 staging operations to provide separate antennas for cruise, entry and the surface. The HGA operates only on the surface of Mars.

The Propulsion S/S is a classic hydrazine mono-propellent system operating in blowdown mode using four titanium tanks w/propellant management devices (built by PSI), 8 1 lbf thrusters (built by Olin) in 2 clusters of 4 each. The total propellant load is 85kg designed to deliver approximately 130 m/s of delta velocity.

ENTRY, DESCENT AND LANDING SUBSYSTEM DESCRIPTION

Entry, Descent and Landing (EDL) subsystem fundamentally distinguishes Mars Pathfinder from all other planetary missions except for Viking. The challenge of entering another planet's atmosphere and landing on its surface safely, especially given how little we know about Mars, is enormous. EDL is by far the most complex subsystem on Mars Pathfinder. It is made up of 7 elements: aeroshell, parachute, rocket assisted decelerator, bridle, separation systems, altimeter and airbags. These elements are intimately interrelated in design and function. For example, the airbag design is dependent on the landing velocity which is dependent on the altimeter performance and the total impulse of the RAD rockets is in turn dependent on the parachute terminal velocity. All of these elements are tied together by a team of systems engineers and analysts who have developed and exercised a master monte carlo simulation to which predicts performance based on test correlated properties of the EDL pieces working with all the uncertainties of the hardware, software and the natural environment.

The aeroshell (heatshield and backshell, built by Lockheed-Martin Aerospace) is derived from the Viking design and uses requalified Viking heritage materials. The parachute (built by Pioneer Aerospace) is based on the disk-gap-band Viking design with a larger band and higher strength riser materials. The rocket assisted deceleration (RAD) subsystem uses 3, 2500 lbf-sec impulse rockets, based on Titan SRB separation motors and using space qualified propellant. The bridle subsystem (built at JPL) uses a commerical rate limiter (built by ,) and kevlar rope to lower the lander 20m below the backshell.

The airbag subsystem (designed by JPL and built by ILC Dover) is a completely new design which uses gas filled (from gas generators built by Thiokol) Vectran bags, which envelope the lander and cushion its landing at about 25 m/s on the rocky Martian terrain. This design is based on many drop tests conducted at Lewis Research Center's Plum Brook Station which boosts the world's largest vacuum chamber with 120 ft of vertical height and 100 ft working floor space. These tests involved dropping full scale bags (overall diameter about 5 m), at Mars atmospheric pressure (1 % of Earth) onto a rock field representative of the expected landing site. Vertical drop speeds of 15-28 m/s were conducted. In order to simulate the horizontal velocity in a vertical drop test, the rocky surface was rotated 60% into the air. A final set of retraction and lander deploy tests are conducted under realistic rock strewn terrain and cold (-100 C) conditions.

IMPLEMENTATION

The programmatic challenges of this spacecraft are significant. The development period is 3 years and the hard cost constraint is \$171 M (real year \$), of which the flight system will likely be about \$135M. The logical comparison is to Viking which was a 6 year development which today would cost >\$3B. The fundamental difference is in classification and approach to risk. On Pathfinder significant risks are being taken, including single string architecture, non-class

S electronic parts, limited documentation. New ways to doing business, that harken back more than 20 years, are being used that significantly reduce development time and control costs.

The key to success in the "faster, better, cheaper" genre, where one must take significant risks but still not fail, is **to do things differently.** The, following are key elements of Pathfinders implementation approach which has worked well so far.

"Capabilities Driven" approach to system and subsystem designs. "Requirements" are based on capabilities. Team pushed back on "requirements" driving cost/risk/schedule. Inspite of this restriction we have an excellent science mission.

The right team of motivated people can do almost anything. The excitement about the mission, new ways of doing business and willingness to give people lots of authority/responsibility attracted many of JPL best and brightest. I heard from many people that this is the best project they'd every worked on. Occasionally, old "business as usual" attitudes and practices had to be identified and corrected.

Use **a flat organization, with its inherently better communication.** The management team was on a first name basis with nearly every member of the team, including Cog. E's, designers and technicians. Key decisions were able to be made quickly because the management team knew the status, problems, problem ramifications and whether the people involved were right to fix the problem. **Co-location of management, systems,** AIM (H/W, S/W, I&T), **Ground Data System is a major factor in our success.**

Hands-on management is essential for FBC **projects.** The FSM is technically involved and personally managed the mass, budget and schedule and was able to make rapid decisions to give needed resources/flexibility to S/S's as problems came up. Extensive trade studies were not needed to make baseline changes.

An atmosphere of openness and honesty between the Project and doing organizations is required for teamwork and teamwork is essential for success. An us vs. them mentality hides problems. Technical and budget problems can be resolved quickly in a team environment. Everyone knew the state of the budget. When people needed reserves they got them. When budget cuts were needed we worked together on scope reductions (i.e. no arbitrary cuts of 10%).

High reliance on individual team members knowledge, communication skills and comittment to make sure things don't fall through cracks saves money in documentation and people. But some things did fall through cracks, particularly in complex interface definitions. However, the savings (>$1M) far outweighed to costs.

Utilize need driven and less formal documentation. Memos, vugraphs, sketches vs. project documents has worked well. S/S generated level-4 documents as they needed. Engineering change request (ECR) process was run by S/C Systems team. Total number of ECR's is about 15. FSM Baseline Memo communicated most changes.

ICD's (mechanical, electrical and informational) got early focus but it wasn't enough. One person, with the greatest stake owns each ICD (MICD: Mech. Sys., EICD: S/C Systems, IICD: AIM). The design and interface definition process has to proceed in parallel with a constant ebb and flow of progress-problems-resolution in most areas. The fact that some of the most complex interfaces are with new subsystems (EDL, science) and/or are contracted tasks makes the problems all the more difficult, **ICD job requires project support at systems-level, experienced engineers who know what an ICD must contain and a dedicated person to personally make sure the hardware being built matches the ICD's (yes, go and check that the Cog's are building to the ICD's).**

Extensive use of peer reviews for all FS system, subsystem and assembly-level reviews works much better than a few formal reviews. Major formal reviews never added anything. Only outside review should be IRR, (to satisfy HQ we're on track, period). Reviews are forcing function for work to be done on time. Peer reviews bring in technical experience w/o a lot of overhead or worrying about looks. FS had about: 100 peer reviews. Used system of capturing real time advisory, directives and *M* with a review of all items at end of review to reach concensus (avoids RFA syndrone). Traditional S/S MMR's held with Cog. E's, line management & project management provide common view of progress/problems and allowed everyone to interact on solutions.

Experienced procurement manager who knows the process/people and can lubricate/council is essential for any fast project. Streamlined procurement processes for small procurements and electronic parts has worked very well, especially for electronic parts, RFP pre-ship reviews work well. Makes for a parallel rather than serial process of the package, including spec., SOW, CDRL's, which is faster and more thorough. The use of the red/yellow/green procurement summary was good HQ, project and S/S metric and was occasionally useful as a mot ivator when shown to vendors.

Early industry involvement and teaming essential for new developments. Partnership with industry under fixed price contracts (e.g. computer, parachute, RAD rockets, aeroshell) went very well, Although major aerospace contractors don't tend to like fixed price contracts we probably got the most product for the money.

Understanding risks early and developing a mitigation strategy is essential. Our single string planetary mission with Class B parts is gutsy but doable. Pathfinder is enabled by a short mission, simple cruise spinner, low radiation environment, lots of test time (planning for 1000-2000 hrs on electronics before flight) Risk avoidance through planning has identified key risk areas, risk level and mitigation approaches. We are intentionally hardware rich, with H/W and S/W testbeds for development & trouble shooting. System, inter-subsystem and subsystem failure modes, effects and criticality analysis (FMECA) were performed between PDR and CDR to weed out design flaws.

Risks are controlled by use **of qualified parts, materials and processes, use of adequate design margins.** We followed a strategy of design resiliency and descope options including all system margins (mass, power, memory, processor speed...). Unpredictable risk is managed by maintaining programmatic reserves. The initial budget reserve was >30% and initial schedule reserve was >20 weeks in assembly, test and launch operations (ATLO) phase. ATLO started 18 months before launch, which is very generous for a fast paced project.

Utilized a single team of S/W engineers (8-1 O) for all flight S/W (received some modules but own entire final procduct). **Used S/W module PDR's instead of rigorous top down requirements flow.** Peer review process lets S/W designers work with users and increases their knowledge and ownership of the S/W product. Use of object oriented architecture has worked well.

G & C analysts developing algorithms, coding, testing and providing prototype code to FSW was very successful and motivating to G & C team. Got good code very early.

Commercial, real-time, operating system (VxWorks) allowed early architecture and design work, However, it is slow due to large overhead. Need 20 MIP-class performance in order to avoid code optimization.

Largely single string S/C requires much less fault protection design and development. Traditional fault protection is much simpler with only 2 major algorithms (10-12 total): command loss and battery charge control.

Adequate budget reserves are essential. A **time phased plan for acceptable reserve usage is also necessary.** FSM and PM agreed on how much $$ could be used over a certain period and FSM worked within that. The development and maintenance the "Estimate of Reserves Needs and Usage Summary" (attached) was very useful in anticipating/planning reserve needs and metering out reserves at a sustainable pace. HQ and review boards liked it and found it a credible way to explaining reserve usage plan. The key is convincing the bean counters that "estimate of reserve needs" is different than hard liens.

CONCLUSION

Mars Pathfinder is living FBC. Faster: 3 years from project start to launch. Better: 3 spacecraft in one: cruise, entry and lander plus a rover. Cheaper: $171M vs >$3000M for Viking.

FBC requires taking more risks without significantly increasing likelihood of failure. You have to do things different but be smart about it. Mitigate technical risks with design margins and extensive testing.

FBC requires an enormous personal commitment on the part of the entire team especially the lead system engineers and technical managers. Long hours, high pressure. Management has to be ruthless in getting the right people and getting rid of the wrong people. Personal rewards are in the challenge and doing something many people think can't be done. The key is the quality and quantity of talented, energetic and motivated people.

Brian Muirhead has worked on various spacecraft, science instrument and technology projects including Galileo, CRAF/Cassini, Mars Rover Sample Return. He has lead 2 precursor FBC developments at JPL: the SIR-C Antenna Mechanical System (which flew on STS 59 and 68) and the MSTI mechanical subsystems. He has a BSME from the [University of New Mexico and an MSAE from Caltech.

CRUISE STAGE CONF GURATION

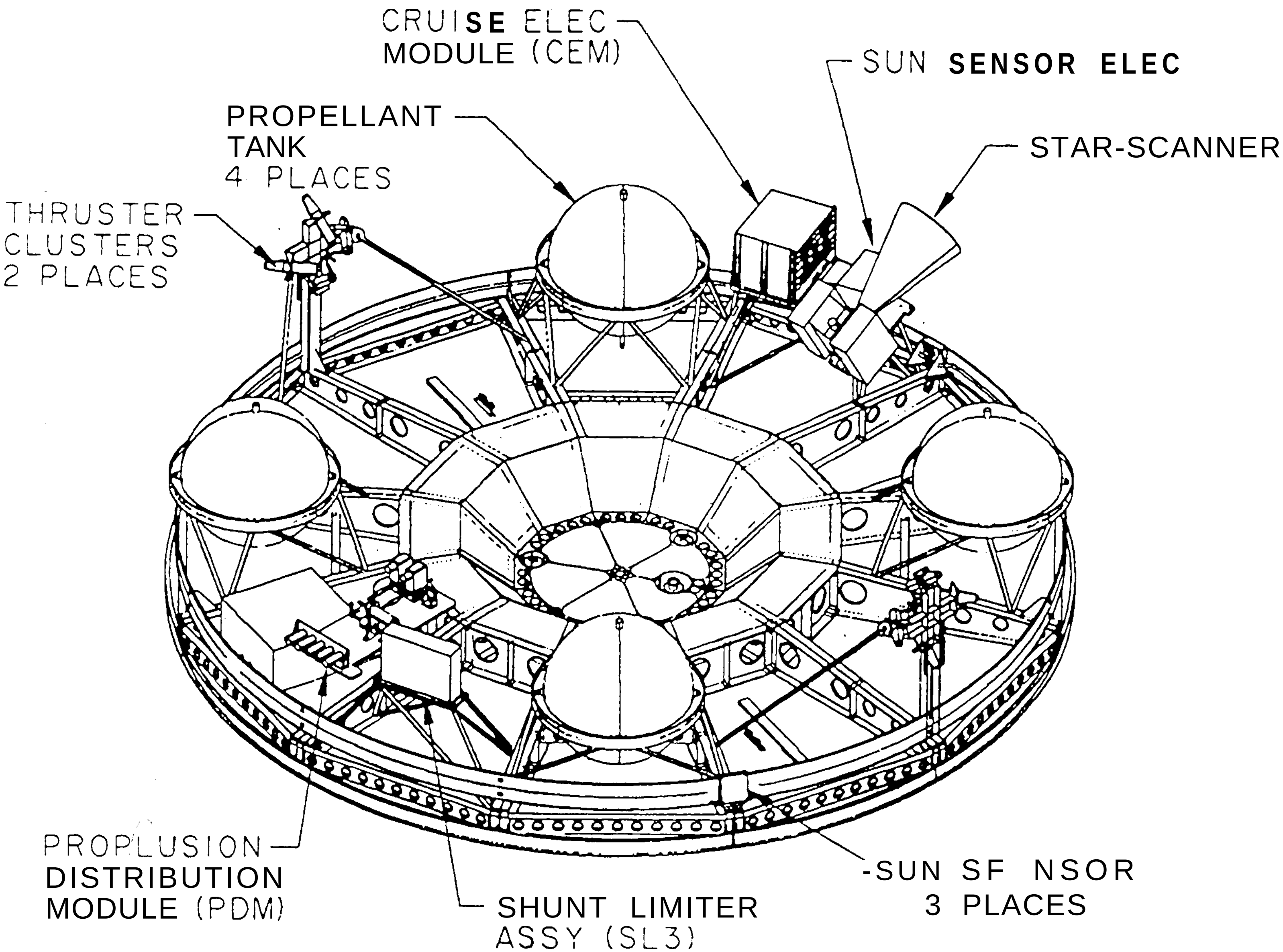

FIGURE 1

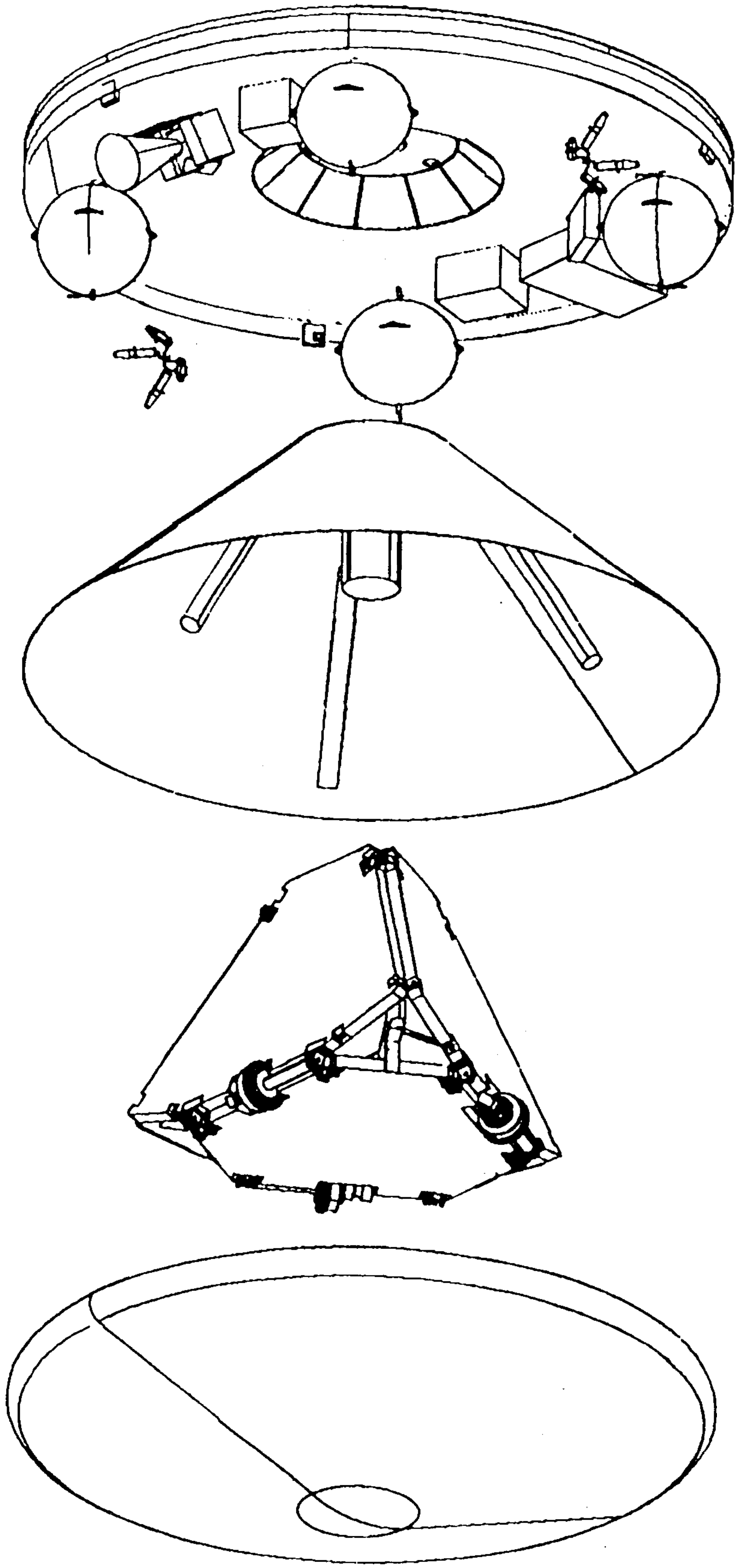

FIGURE 2

LANDER DEPLOYED CONFIGURATION

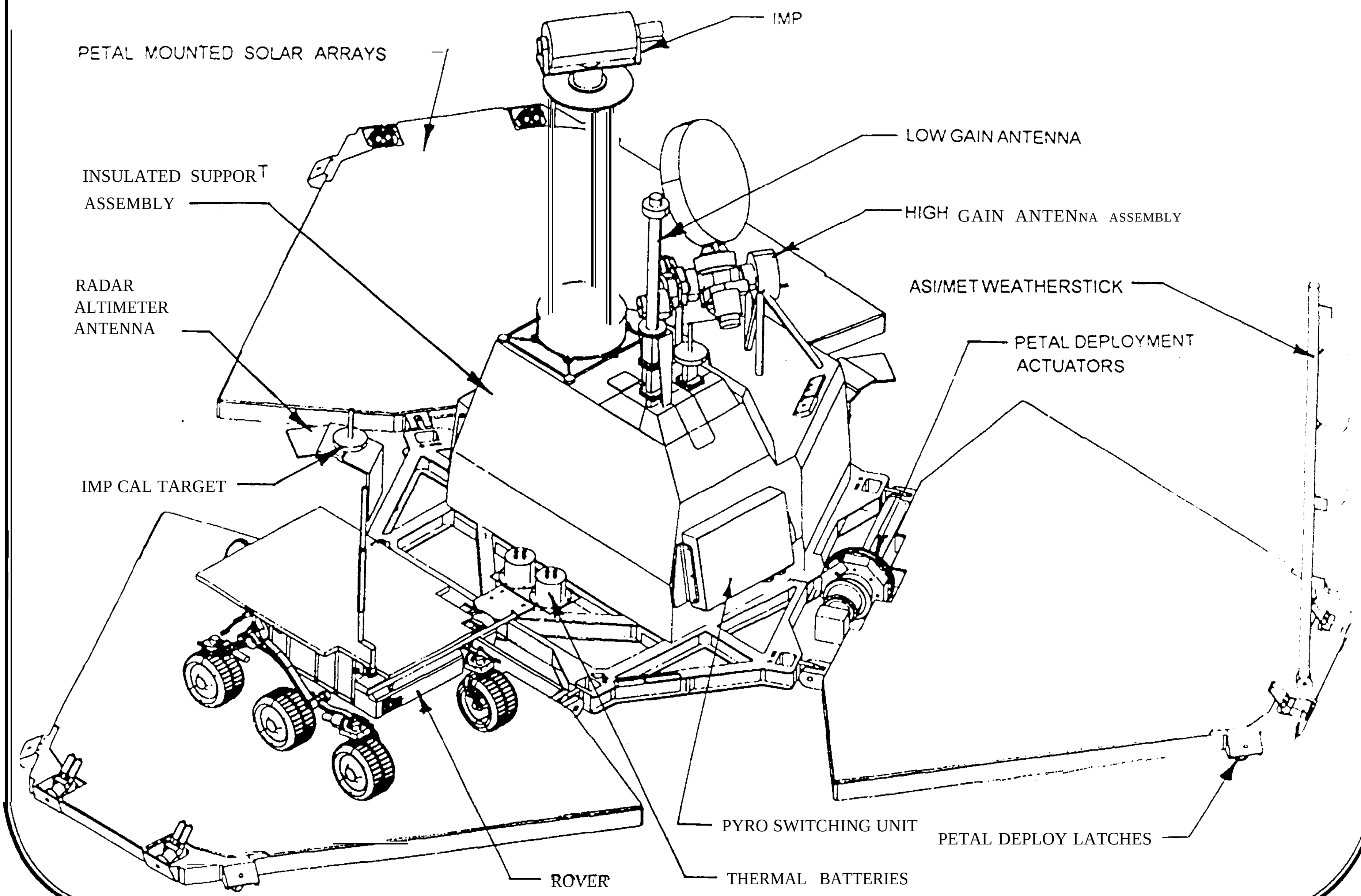

FIGURE 3

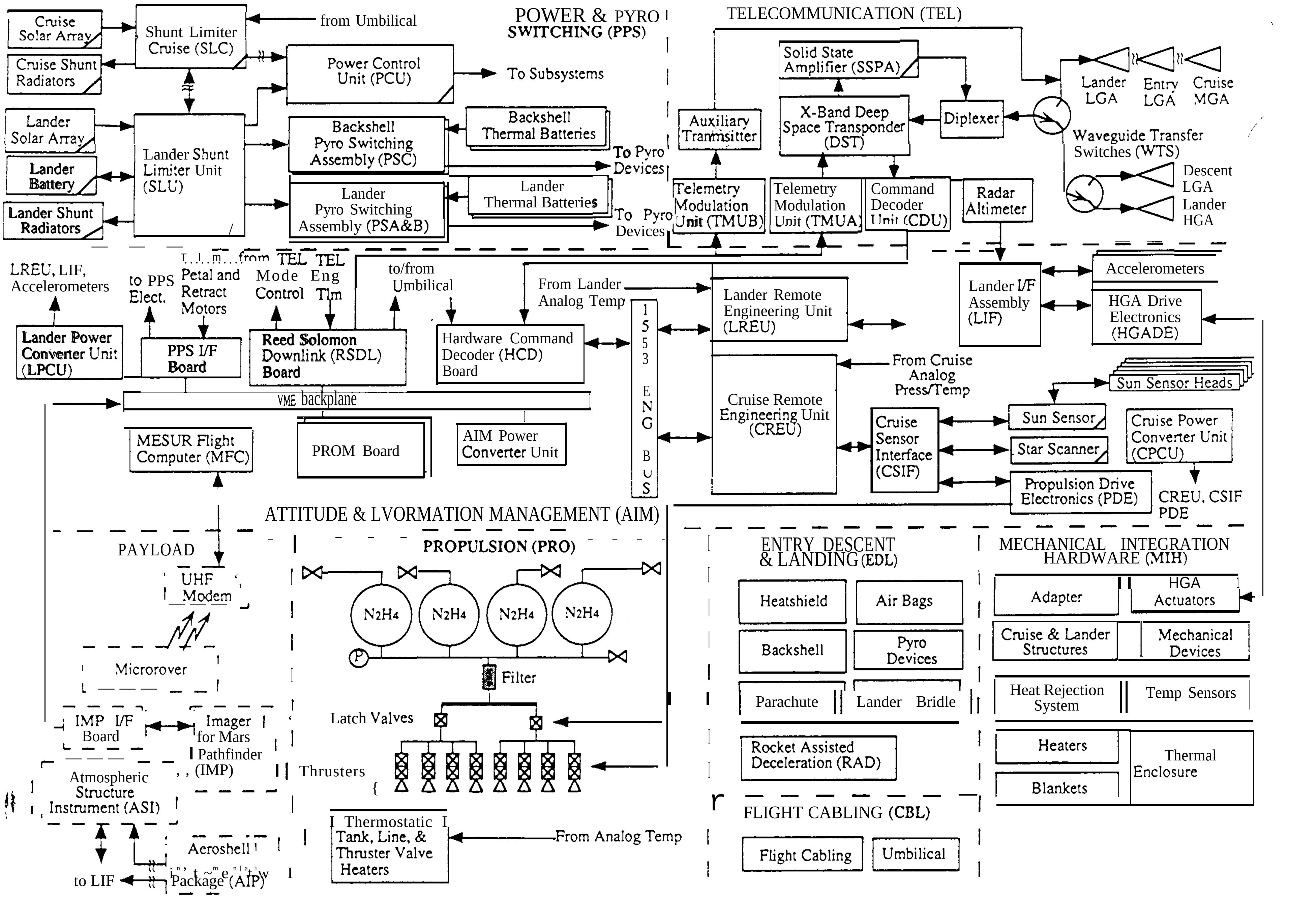

FIGURE 2-3 FLIGHT SYSTEM FUNCTIONAL BLOCK DIAGRAM

January 1995

FIGURE 4

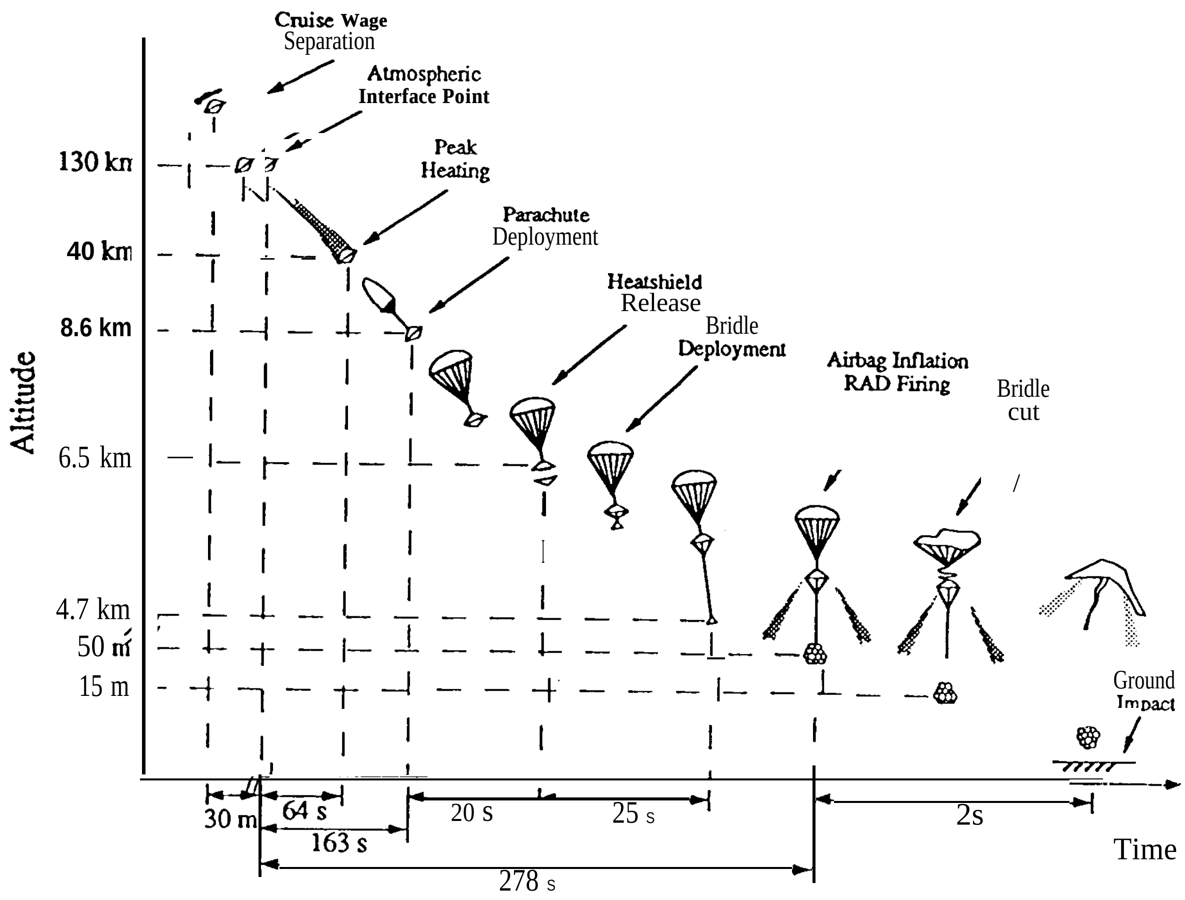

Figure 5. Entry, Descent and Landing Sequence of Events